

Numerical Studies of Sea Surface Scattering And Emission

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LONG-TERM GOAL

The long term goal of this project involves developing improved models for sea surface thermal emission and grazing angle scattering through the application of both analytical and efficient numerical methods for electromagnetics and hydrodynamics. These models can then be applied to improve clutter removal for radar systems operating at sea as well as to improve microwave active and passive remote sensing of the ocean surface.

SCIENTIFIC OBJECTIVES

Although validated approximate models exist for microwave scattering from the sea surface at moderate to large grazing angles, no theory has been completely accepted for scattering at low grazing angles. The effects of breaking waves and hydrodynamic modulations have been established but their relative contributions and the physical scattering mechanisms remain a subject of debate given the uncertainty in approximate methods previously applied. This project seeks to apply numerically exact models to avoid the limitations of standard approximate methods so that the influence of different scattering mechanisms can be conclusively established in this angular regime, allowing realistic parametric models for remote sensing retrievals and clutter rejection to be created.

Analytical theories are also available for the prediction of microwave sea surface brightness temperatures and have shown considerable success, but the underlying physics of the emission process remains unclear. Efforts in emission theory are focusing on studies and extension of the analytical models to provide improved understanding of the phenomena producing emission signatures.

APPROACH

The approach to the scattering problem is to apply recently developed numerical models for scattering and hydrodynamic evolution of three dimensional rough sea surfaces. Several efficient models for the computation of scattering from a rough surface have been demonstrated in the literature through one dimensional surface studies, including the canonical grid [1], fast multipole [2], forward-backward [3], and operator expansion [4] methods. However, studies for ocean-like surfaces rough in two directions have been much more limited due to the increased computational complexity involved [4-6]. In addition, the grazing angle regime is very challenging numerically, given the increased contribution of edge effects for finite surface sizes. Inclusion of the effects of finite surface conductivity is also critical, since many proposed scattering mechanisms depend on finite conductivity effects. A numerical approach to the hydrodynamics problem is being applied as well, following the development of [7]. This model

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incorporates many non-linear aspects of hydrodynamic evolution, and should therefore help in determining the influence of these effects on grazing angle scattering.

Analytical model studies of sea surface emission are focusing on the small-slope theory [8], which has been shown to be identical to small perturbation theory for emission calculations. An extensive debate in the community is currently taking place with regard to the source of azimuthal harmonic variations of ocean brightness temperatures, particularly the relative influence of large and small scale wave structures. Uncertainties in the ocean surface directional spectrum make this a difficult question to resolve conclusively, but studies of the emission theory can reveal the extent to which asymmetry in differing length scales can contribute to observed harmonics independent of the directional spectrum model used. Extension of current second order theories to third order also allows insight into measured first azimuthal harmonics of ocean brightness temperatures.

WORK COMPLETED

Several new developments have occurred in FY 98. Studies of several numerical methods for low grazing angle scattering calculations led to the development of an improved method for the one dimensional surface problem, based on a combination of a steepest descent type multipole algorithm with the iterative forward-backward method [9]. The resulting code has an order (N) complexity, and allows much rougher surfaces to be studied than the canonical grid method. A one dimensional version of the non-linear hydrodynamics code [7] was also completed, and applied in an initial doppler spectrum study for time evolving surfaces and an initial SAR imaging study of rough surfaces at near grazing angles. The efficiency of the one dimensional scattering models applied make these more detailed simulations possible.

Monte Carlo simulations of near grazing angle backscattering from two-dimensional surfaces have also been performed [10], down to 10 degrees grazing angle. The improved forward-backward method is currently being extended to the two dimensional surface case, so the canonical grid method for impedance boundary surfaces developed in the previous project year was applied in the study. Accuracy tests of the code showed that a higher sampling rate and surface size of 128 by 32 wavelengths were required at 10 degrees grazing, leading to a total of approximately 2 million unknowns in the simulation for each realization. The size of this problem exceeded the limitations of a single workstation, so a parallel scattering code was developed for its solution, using four workstations for each realization. Extension of the hydrodynamics code to two dimensional surfaces is also nearing completion, so the combination of numerical scattering and hydrodynamics models for two dimensional surfaces should allow some new insights to be obtained in the coming year.

Emission theory studies [11] have carefully examined predictions of the small slope theory of ocean surface brightness temperatures. It has been found that emission harmonics can be represented as a sum of contributions from each (length scale) component of the ocean wave spectrum, weighted by a "weighting function" which is a property of the radiometer frequency, observation angle, and surface permittivity. Studies of the weighting functions therefore provide information on the sensitivity of emission harmonics to differing length scales of the ocean spectrum, independent of the ocean spectral model used. Extension of the small slope theory to third order, so that first harmonics can be consistently predicted, is currently in progress, and results to date are demonstrating the importance of the ocean surface bispectrum (a third order statistic). A numerical implementation of the small slope theory has also been developed, which allows arbitrary order results to be obtained.

RESULTS

A Monte Carlo study of 14 GHz low grazing angle (down to 1 degrees grazing) backscattering from one dimensional surfaces [9] of length 8,192 wavelengths similar to reference [12] was repeated but with much rougher surfaces (wind speed 10 m/s, at which the $k \cdot \text{rms height}$ product is 158). Similar to reference [12], results showed a general failure of all analytical theories in this angular region, but a similar physical behavior to the composite model: increasing HH cross sections with wind speed while VV remained relatively constant. Even for these very rough surfaces, however, polarization ratios remained significantly less than unity, demonstrating again that the use of linear hydrodynamic surfaces produces no significant sea spike or super event behaviors. Studies using surfaces obtained from the non-linear hydrodynamic code are in progress and should clarify scattering effects captured by the hydrodynamic model of [7].

Figure 1 below illustrates two dimensional surface Monte Carlo averaged backscattering cross sections obtained from the parallel canonical grid code with the impedance boundary condition [10]. Scattering from Pierson Moskowitz surfaces with a $k \cdot \text{rms height}$ product of 2.86 is illustrated at 14 GHz. Also included are predictions of the composite surface model. As in the one dimensional surface case, the composite surface model is shown to provide reasonable predictions at 10 degrees grazing, even for cross polarized cross sections, although it is expected that performance should degrade at smaller grazing angles. Efforts to extend simulations to lower grazing angles are currently in progress, and the improved forward-backward method when completed should allow studies for rougher surfaces.

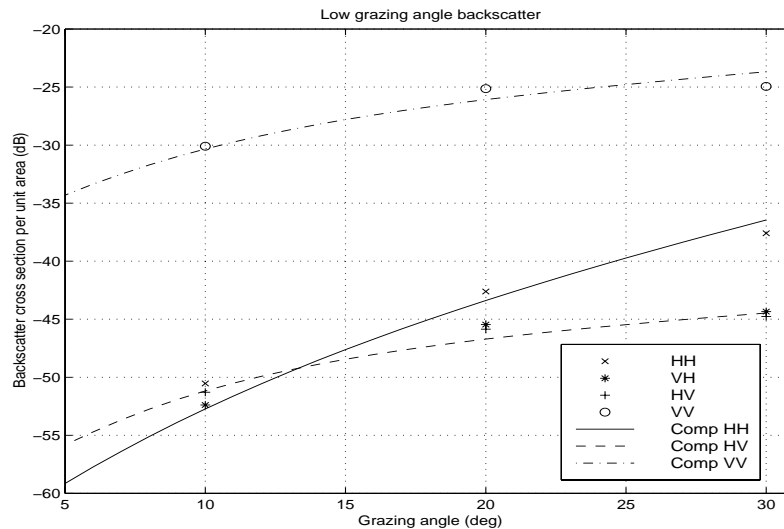


Figure 1: 14 GHz moderate grazing angle backscattering from a two dimensional Pierson-Moskowitz ocean surface. Surface sizes of 128 x 32 wavelengths were used in the simulation, with 2 million unknowns.

Figure 2 below is a plot of the “weighting” function from the small slope emission theory for second azimuthal harmonics of ocean brightness temperatures in all four polarimetric brightnesses (h, v, U, and V). A radiometer polar angle of 60 degrees is assumed and a surface permittivity corresponding to sea water at 14 GHz. The horizontal axis of the plot corresponds to the logarithm of ocean wave length scale relative to the electromagnetic wavelength, with larger gravity type waves to the right and smaller

capillary type wave to the left. Again these weighting functions are multiplied by the second harmonic of the ocean surface curvature spectrum (which is also a function of length scale) and integrated to obtain predicted brightness temperature second azimuthal harmonics. The curves of this plot demonstrate the increased sensitivity of emission harmonics to length scales in the “critical phenomenon” region around the electromagnetic wavelength, but significant sensitivities to larger scale waves on the surface are observed as well due to the constant nature of the weighting functions at large length scales. These results demonstrate that ocean length scales both comparable to and much larger than the electromagnetic wavelength can contribute to observed emission harmonics. More detailed results are described in [11].

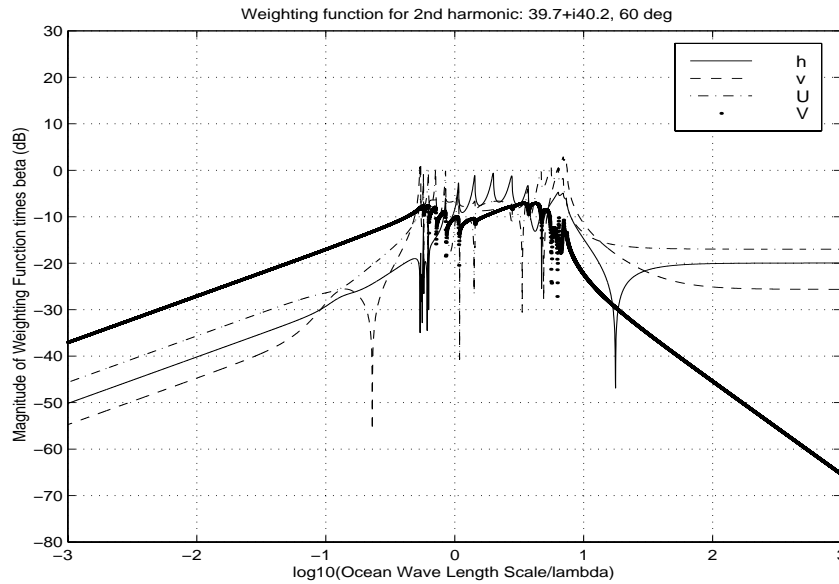


Figure 2: Second harmonic emission weighting functions for $e=39.7+i*40.2$ at 60 degrees observation.

IMPACT/APPLICATION

Insights into emission physics obtained are expected to have impact in methods for passive remote sensing of ocean wind vectors, needed in the design and application of the Conical Microwave Imaging sensors for the NPOESS next generation of weather satellites.

Scattering codes developed for this project will have impact in any technology where rough surface scattering has effects. Although the primary application for the project is the use of radar over the ocean surface, the models developed can also be applied to study soil surface scattering effects on ground penetrating radar and soil moisture remote sensing systems, synthetic aperture radar remote sensing of the ocean, and remote sensing of forest and vegetated areas.

TRANSITIONS

Results of these projects have been communicated at several ONR sponsored workshops. It is expected that project results will be extensively applied in the design of future sensors in the coming years.

RELATED PROJECTS

Current related projects include an ONR sponsored project with Dr. Bob Burkholder on numerical and hybrid methods for computing scattering from targets above a rough surface boundary. A second related project involves numerical and experimental studies of soil surface scattering effects on ground penetrating radar systems, in which many of the models developed in this project are being applied.

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